

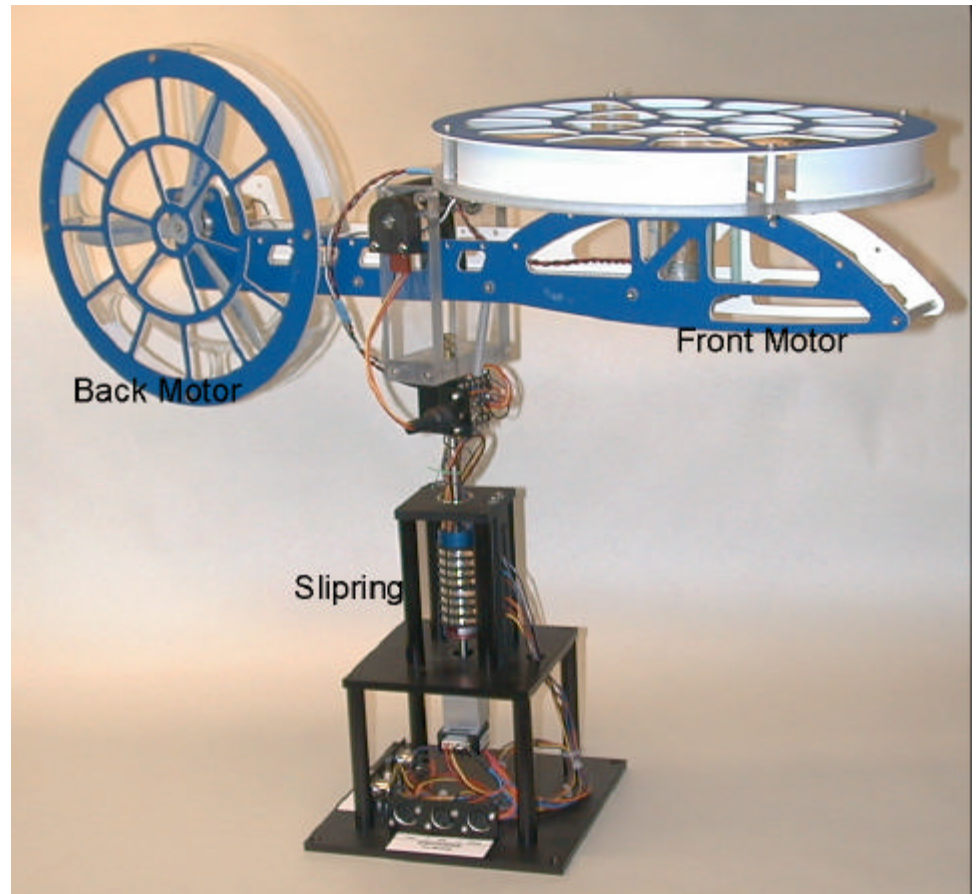
# **2D Helicopter Experiment**

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## 2D HELICOPTER EXPERIMENT

### 1.0 SYSTEM DESCRIPTION

The 2D flight simulator experiment shown in Figure 1 consists of a helicopter model mounted on a fixed base. The helicopter model has two propellers driven by DC motors. The pitch propeller and the yaw propeller are used to control the pitch and yaw of the model. Motion about the two degrees of freedom is measured using two encoders. The purpose of the experiment is to design a controller that allows you to command a desired pitch and yaw angle. You will also examine the performance of the system with an operator in the loop. A joystick is supplied that allows you to command the motors in open loop in order to compare human operator performance with computer control. The joystick will also be used to provide the operator with a closed loop controller which improves operator performance and makes the system easier to use.



Electrical signals and power from the pitch encoder and the two motors are transmitted via a slipring. This allows for unlimited yaw and eliminates the possibility of wires tangling on the yaw axis.

**Before you proceed with the experiment please wire the system as described in sections 5 & 6.**

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### 2.0 MATHEMATICAL MODELLING

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A complete mathematical model including propeller dynamics and forces generated by the propellers is very difficult to obtain. We will instead develop a simplified model.

Consider the two DOF diagram shown in Figure 2. The pitch propeller is driven by a DC motor whose speed is controlled via input voltage  $V_p$ . The speed of rotation results in a force that acts normal to the body at a distance  $R_p$  from the pitch axis. The rotation of the propeller however also causes a load torque  $T_p$  on the motor shaft which is in turn seen at the yaw axis (parallel axis theorem). Thus rotating the pitch propeller does not only cause motion about the pitch axis but also about the yaw axis. Similarly, the yaw motor causes a force  $F_y$  to act on the body at a distance  $R_y$  from the yaw axis as well as a torque  $T_y$  which is experienced about the pitch axis. The simplified equations of motion are then given by:

$$\begin{aligned} J_{pp} \ddot{p} &= R_p F_p + G_p(T_y) + Fg(p) \\ J_{yy} \ddot{y} &= R_y F_y + G_y(T_p) \end{aligned}$$

where:

$p$  is the pitch angle relative to the horizontal axis (0 is horizontal body) Positive is going up

$y$  is the yaw angle (reference is not relevant. Positive is defined CCW looking from above)

$F_y$  and  $F_p$  are the forces generated by the propellers and are functions of  $V_p$  and  $V_y$

$h$  is the vertical distance from the centre of mass to the pivot point ( $h > 0$ )

$R_c$  is the horizontal distance of the centre of mass from the pivot point ( $R_c > 0$  by design)

$T_y$  and  $T_p$  are torques at the propeller axes and are functions of  $V_p$  and  $V_y$

$G_y$  and  $G_p$  are nonlinear functions representing the coupling

$J_{pp}$  and  $J_{yy}$  are the moments of inertia of the body about the pitch and yaw axes.

These equations are nonlinear but can be linearized to obtain an equation of the form:

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$$\begin{bmatrix} \dot{p} \\ \dot{y} \\ \ddot{p} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} p \\ y \\ \dot{p} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ L \frac{K_{ff}}{J_{pp}} & L \frac{K_{tb}}{J_{pp}} \\ L \frac{K_{yf}}{J_{pp}} & L \frac{K_{fb}}{J_{pp}} \end{bmatrix} \times \begin{bmatrix} V_p \\ V_y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ G_d \\ 0 \end{bmatrix}$$

where:

$V_p$  is the pitch motor voltage

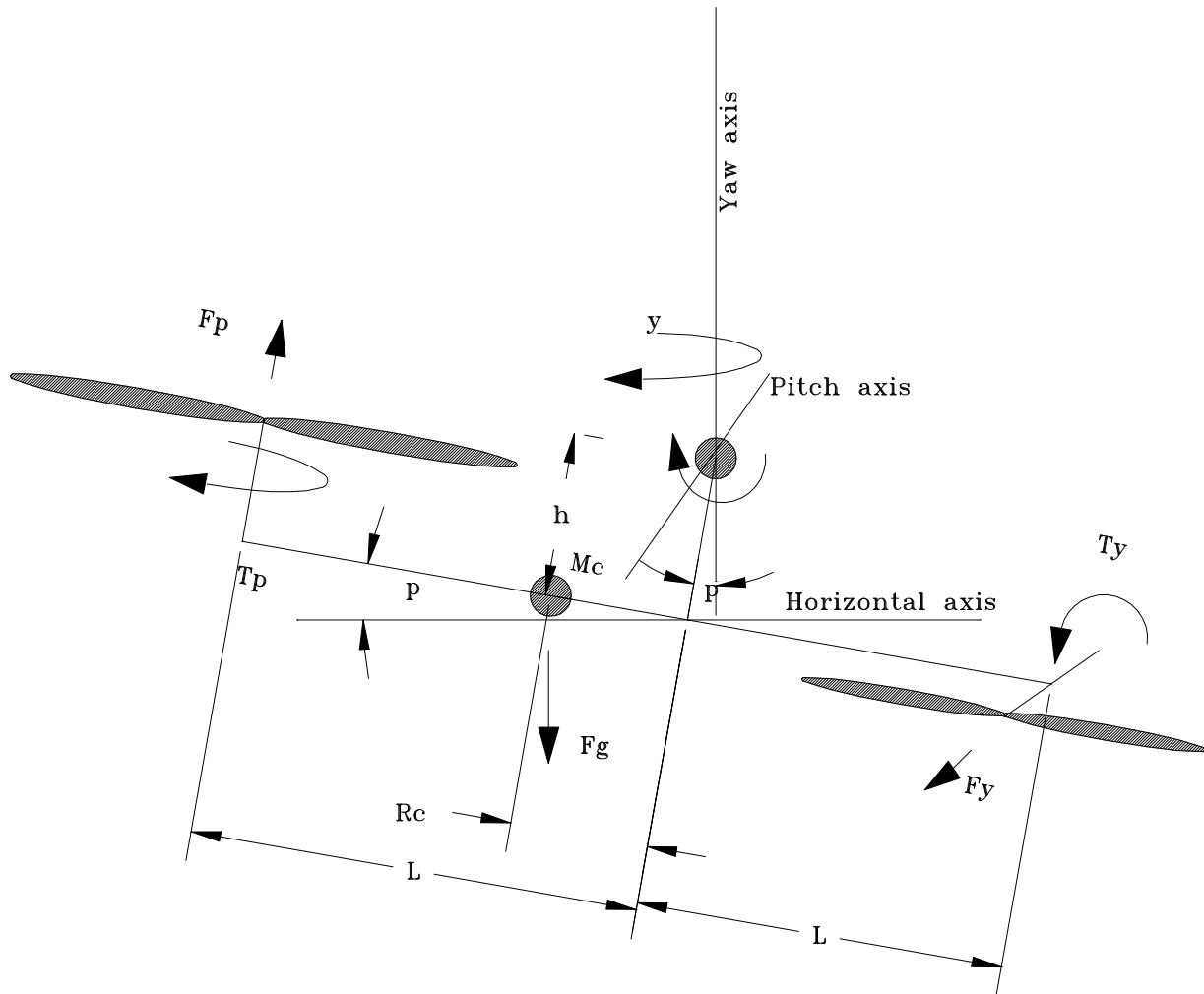
$V_y$  is the yaw motor voltage

$G_d$  is a gravitational constant disturbance

The equations are actually more complex than described above: a) the dynamics of the rotating propellers will also affect the yaw and pitch axes but these effects are considered negligible, b) the response to a voltage input does not result in immediate response of the propeller speeds and thus output force: the time constants of these sub-systems are considered to be much faster than the body dynamics and can also be neglected, c) Centrifugal forces during a yaw rotation will affect the pitch axis and d) air turbulence around the body will result in unknown disturbances.

This model is sufficient to design a working controller. The most important aspects of the

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system are the coupling parameters  $K_{py}$  and  $K_{yp}$  and their SIGNS. Note that a positive pitch voltage results in a pitch but also a negative yaw. The ideal controller would take advantage of this effect in order to obtain an efficient response. For example, when turning right a helicopter pilot pitches up and reduces throttle to the stabilizer (yaw motor) and when turning left, the pilot would pitch down and increase the throttle to the stabilizer.

### 3.0 CONTROL SYSTEM DESIGN

Given that there is a gravitational disturbance term  $G_d$ , we clearly need integrators in the loop. We

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define two new states " and . resulting in the following augmented state space representation:

$$\begin{bmatrix} \dot{p} \\ \dot{y} \\ \ddot{p} \\ \ddot{y} \\ \dot{\alpha} \\ \dot{\zeta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} p \\ y \\ \dot{p} \\ \dot{y} \\ \alpha \\ \zeta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ K_{pp} & K_{py} \\ K_{yp} & K_{yy} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \times \begin{bmatrix} V_p \\ V_y \end{bmatrix}$$

We can now proceed in designing a controller for the system.

The control system designed here is an optimal LQR controller but you may design any controller you wish. The system is supplied with an M file DESIGN.M that obtains an optimal gain given the performance index:

$$J = \int x' Q x + u' R u$$

where Q (6x6) and R(2x2) are positive definite matrices.

The computed gains are automatically converted to the proper units in the m file **d\_heli2d.m**

The gains that result(converted to degrees) from this design are:

$$\begin{bmatrix} K_p \\ K_y \end{bmatrix} = \begin{bmatrix} K_{11} V / ^\circ & K_{12} V \text{ sec} / ^\circ & K_{13} V / ^\circ & K_{14} V \text{ sec} / ^\circ & K_{15} V / \text{sec} ^\circ & K_{16} V / \text{sec} ^\circ \\ K_{21} V / ^\circ & K_{22} V \text{ sec} / ^\circ & K_{23} V / ^\circ & K_{24} V \text{ sec} / ^\circ & K_{25} V / \text{sec} ^\circ & K_{26} V / \text{sec} ^\circ \end{bmatrix}$$

$$= \begin{bmatrix} 0.0697 & 0.0065 & 0.0238 & 0.0024 & 0.0388 & 0.0013 \\ -0.0081 & 0.0612 & -0.0036 & 0.0301 & -0.0042 & 0.0123 \end{bmatrix}$$

**(NOTE THESE GAINS MAY BE DIFFERENT FROM THOSE DERIVED BY THE ACTUAL DESIGN FILES SHIPPED TO YOU  
- THE DESIGN FILE GAINS ARE ALWAYS THE LATEST)**

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### 4.0 RESULTS

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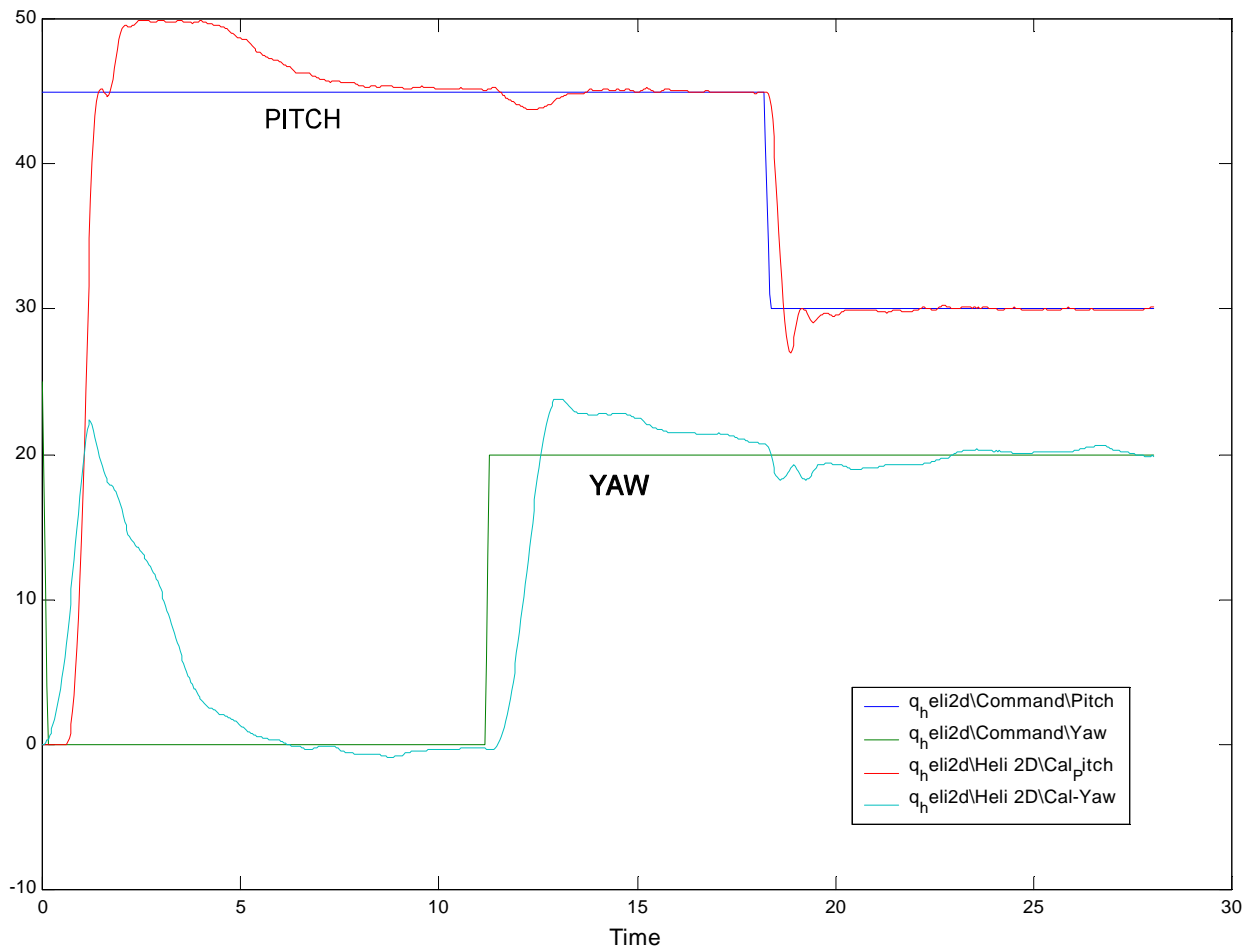
The following files are supplied with the system:

Name	Function	Required SW
d_heli2d.m	Design controller - obtain gains k	Matlab
q_heli2d.mdl	Simulink diagram of controller	SIMULINK
q_heli2d.wcl	Controller that runs using WinCon	SIMULINK, RTW, WinCon
q_heli2d.prj	Project that runs using WinCon	WinCon

The Windows based controller is supplied as SIMULINK diagrams (\*.mdl) and WinCon project (\*.prj) and library file (\*.wcl).

Please read the WinCon manual for details on installing and using WinCon. You can load the controllers straight into WinCon and run them. You can only change parameters if you have SIMULINK and Realtime Workshop. Please refer to the WinCon manual.

**Caution:** Always be ready to stop the WinCon controller by hitting the [Pause] key on the



keyboard in case something goes wrong!

## 5.0 WIRING

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Wire the system as shown. Note that there are two different amplifiers supplied with the system.

The larger amplifier **UPM2405** is used for the pitch motor and is supplied with an output cable labelled "Gain = 5". Use this cable from the "To load" to the Pitch motor. The input voltage  $V_y$  should be limited to 5 volts and is defined to be the voltage applied BEFORE the gain of 5.

The smaller amplifier, **UPM1503** is used for the yaw motor and is supplied with an output cable labelled "Gain = 3". Use this cable from the "To load" to the Pitch motor. The input voltage  $V_y$  should be limited to 5 volts and is defined to be the voltage applied BEFORE the gain of 3.

The measurements for yaw and pitch are obtained by wiring the encoders to the MultiQ board. The resolution for the two axes are 4096 counts per revolution.

- Pitch : Body horizontal



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- Yaw : Starting position

### 6.0 Joystick Input

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The system is supplied with a joystick with two output voltages proportional to the joystick handle angles. The joystick can be wired as shown. The two voltages are applied to A/D channels 2 and 3.

You can use the joystick in two ways: Open Loop or Closed Loop. In open loop, the joystick voltages  $V_{jp}$  and  $V_{jy}$  are used to apply a voltage directly to the motors. This way, the operator commands the throttle directly. Use this mode to examine how difficult it is to control the system in open loop. In this mode the sampled joystick voltages are limited to positive values and then sent out to the motors.

The other mode (which is supplied) of joystick input is to generate a ramp command to the two axes. In this mode, the joystick voltages are not limited to positive values. The voltage is sampled by the program and integrated in software to result in two axis position commands. The rates of integration ( $K_{jp}$  and  $K_{jy}$ ) determine the 'ease' of use of the system. The outputs of the integrators are limited to  $\pm 45$  degrees for pitch and  $\pm 15000$  degrees for yaw. This is the normal mode of operation when you choose controller "1" or "2".

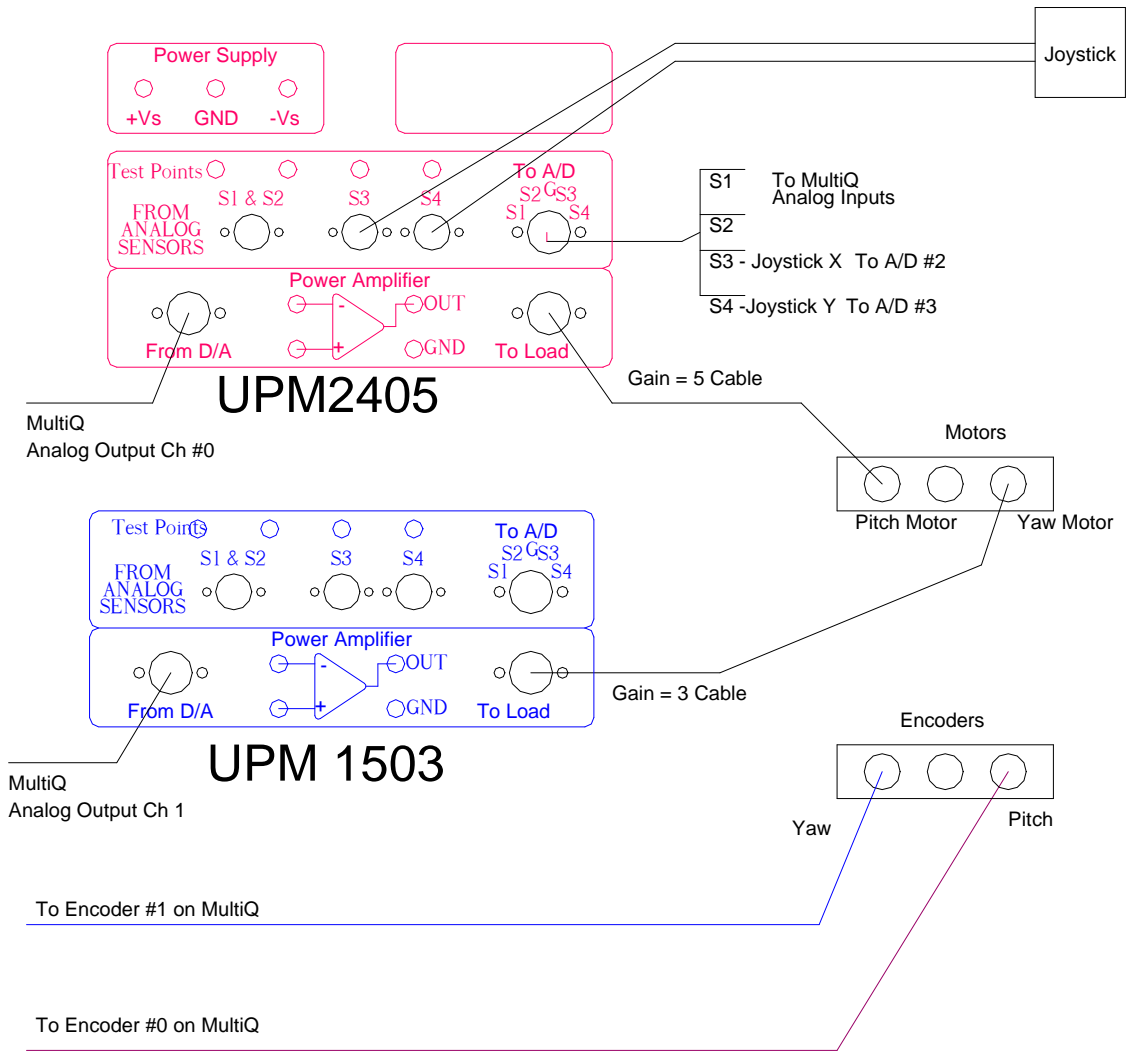
### 7.0 CARING FOR YOUR SYSTEM

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This is an expensive piece of equipment. Be careful and do not abuse it.

- 1) never apply sudden step voltage changes of larger than 1.5 Volts to the pitch motor ( before the gain of 5). By doing so, you are surging more than 5 amperes into the motor and you will eventually damage it.
- 2) Never let the body drop suddenly from mid flight. Always "land" the helicopter.
- 3) Once in a while you will need to clean the contacts of the slipring. Use a contact cleaning solution with a cotton swab and wipe the contact rings. Do not touch the wipers. Keep the system in a clean, smoke free area.
- 4) If the wipers do bend somehow, use a pair of tweezers to bend them back inward to ensure contact. Never force the wipers. Do not use anything bigger or other than tweezers!
- 5) You already have an idea of the feedback gain ranges that will stabilize the system. If the system is unstable, quickly shut it off and redesign your controller.

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### 8.0 System Parameters

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<b>Body</b>	Inertia Jpp	.0307	Kgm <sup>2</sup>
	Total length	40.6	cm
	Distance from pivot to Pitch motor (L)	20.3	cm
	Distance from pivot to Yaw motor (L)	20.3	cm
<b>Pitch Propeller</b>	Diameter	280	mm
	Pitch	178	mm
<b>Yaw Propeller</b>	Diameter	203	mm
	Pitch	152	mm
<b>Pitch Encoder</b>	Counts/rev	4096	
	Resolution	<b>-0.0879</b>	
<b>Yaw Encoder</b>	Counts/rev	8192	
	Resolution	0.04395	
<b>Pitch Motor (using gain = 5)</b>	Force constant	<b>.8722</b>	N/V
	Torque constant	<b>.02</b>	Nm/V
<b>Yaw Motor (using gain = 3)</b>	Force constant	0.42	N/V
	Torque constant	.01	Nm/V